Thermal Energy Storage

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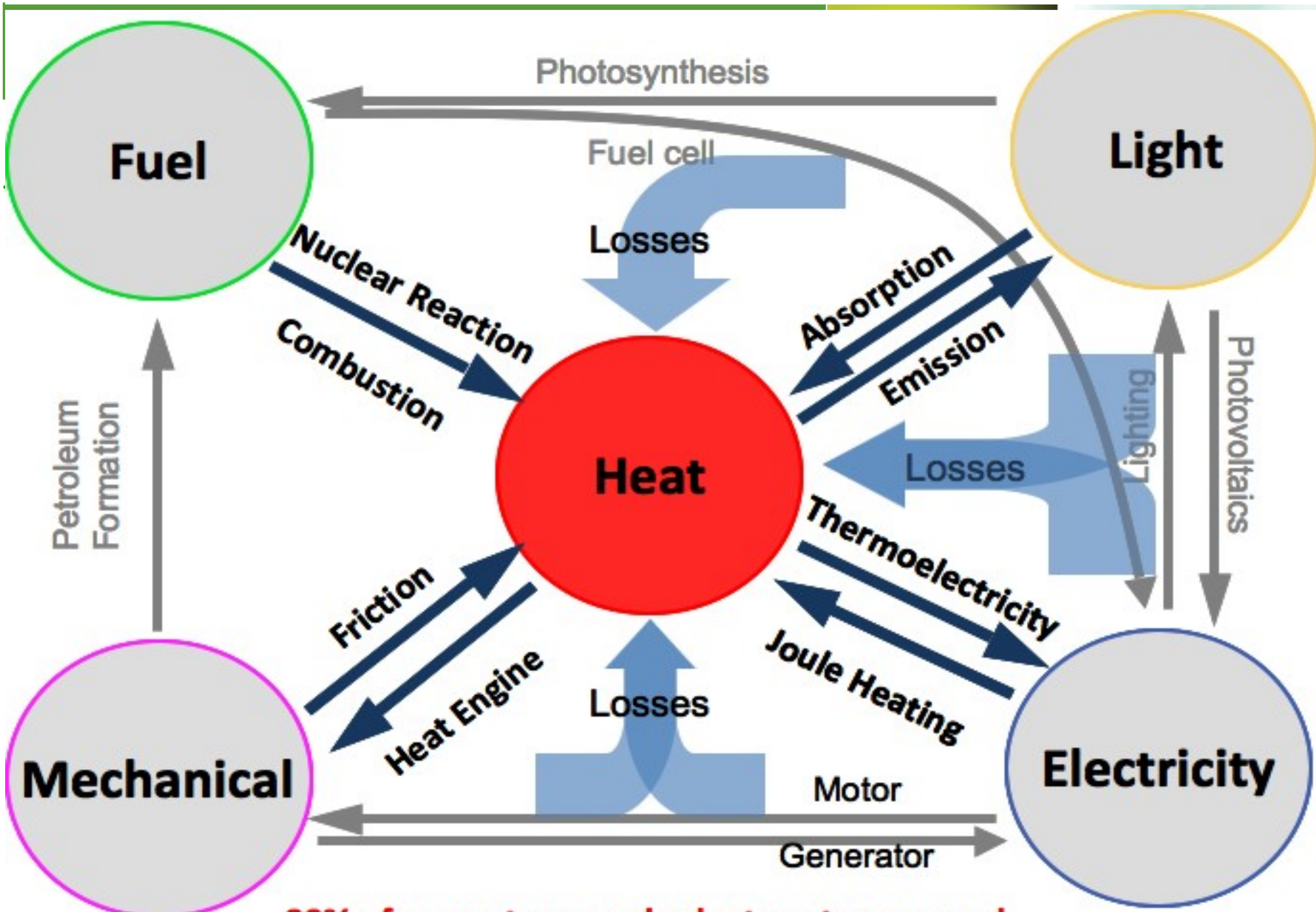
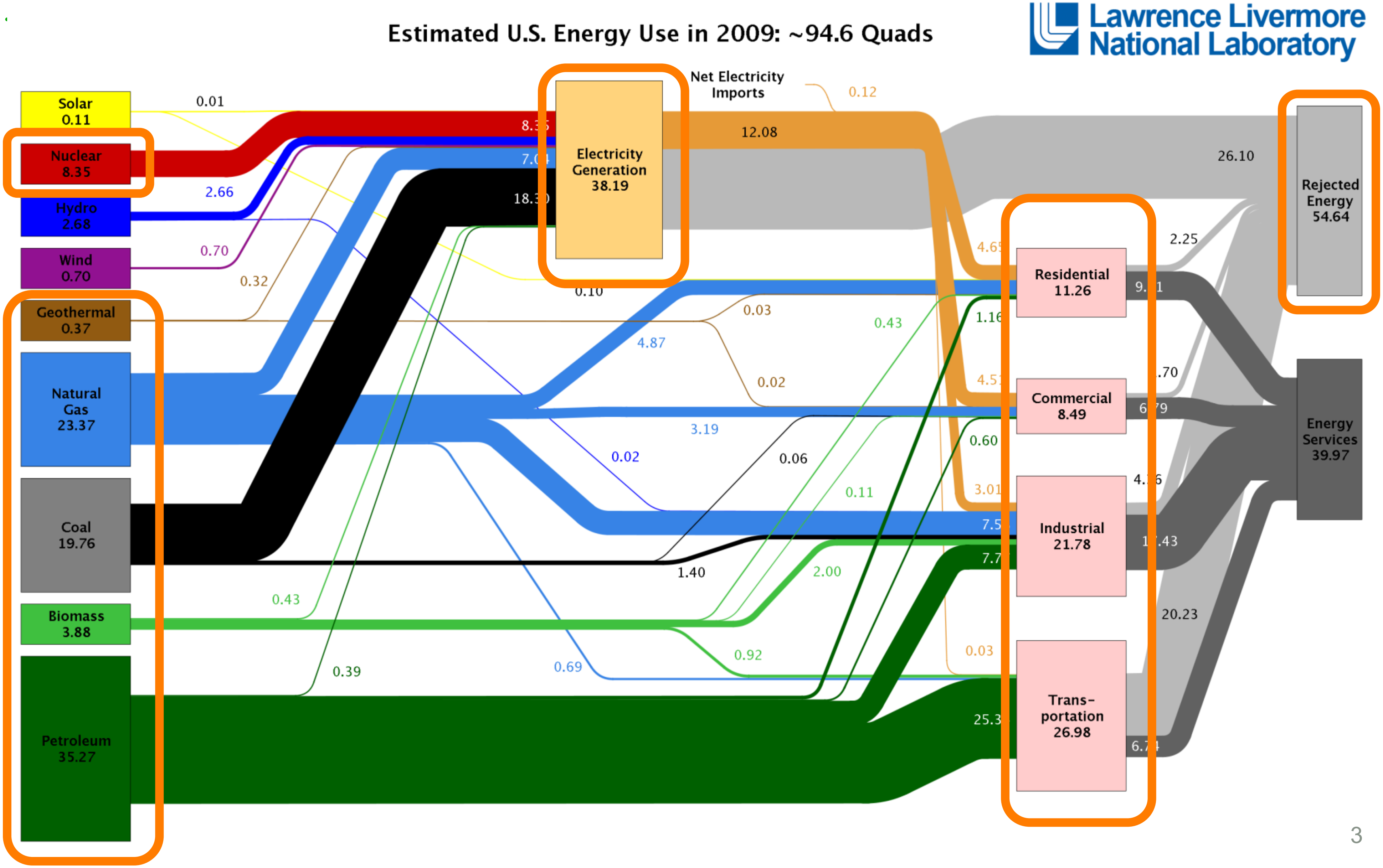
Director, ARPA-E

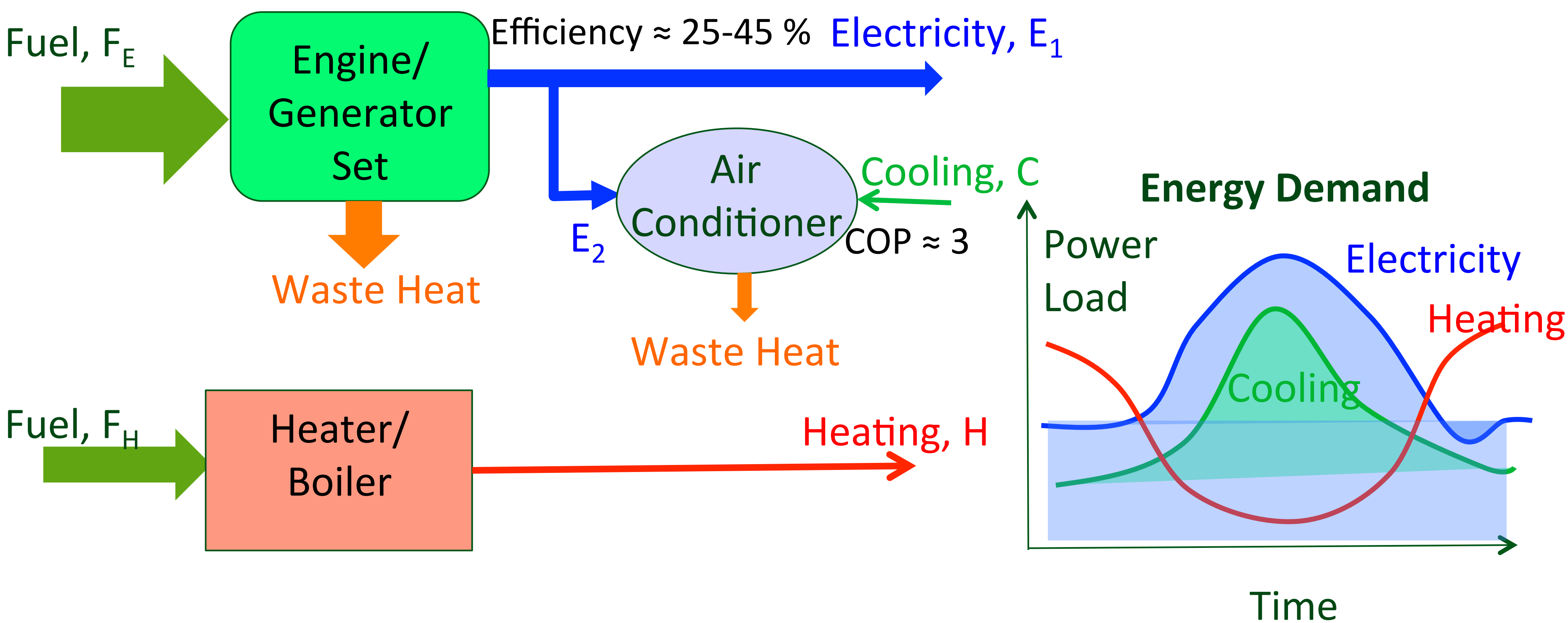


90% of current energy budget centers around
Heat conversion, transmission, and storage

US Energy Diagram



Current System Architecture



Rate of Fuel Use, $F = F_E + F_H$

National Impact of Integrated Energy Supply Systems – Ideal Scenarios

	Today	Heat Coming from Integrated Systems	Heat & Air Conditioning Coming from Integrated Systems
Buildings Site Electrical Load (Quads)	9	9	7.5
Building Site Heat Load (Quads)	10	18	17
Primary Energy Consumption (Quads)	9 x 3.2 +10 = **38.8**	**27**	**24.5**
Primary Energy Saved (Quads)		**11.8 (30%)**	**14.3 (37%)**

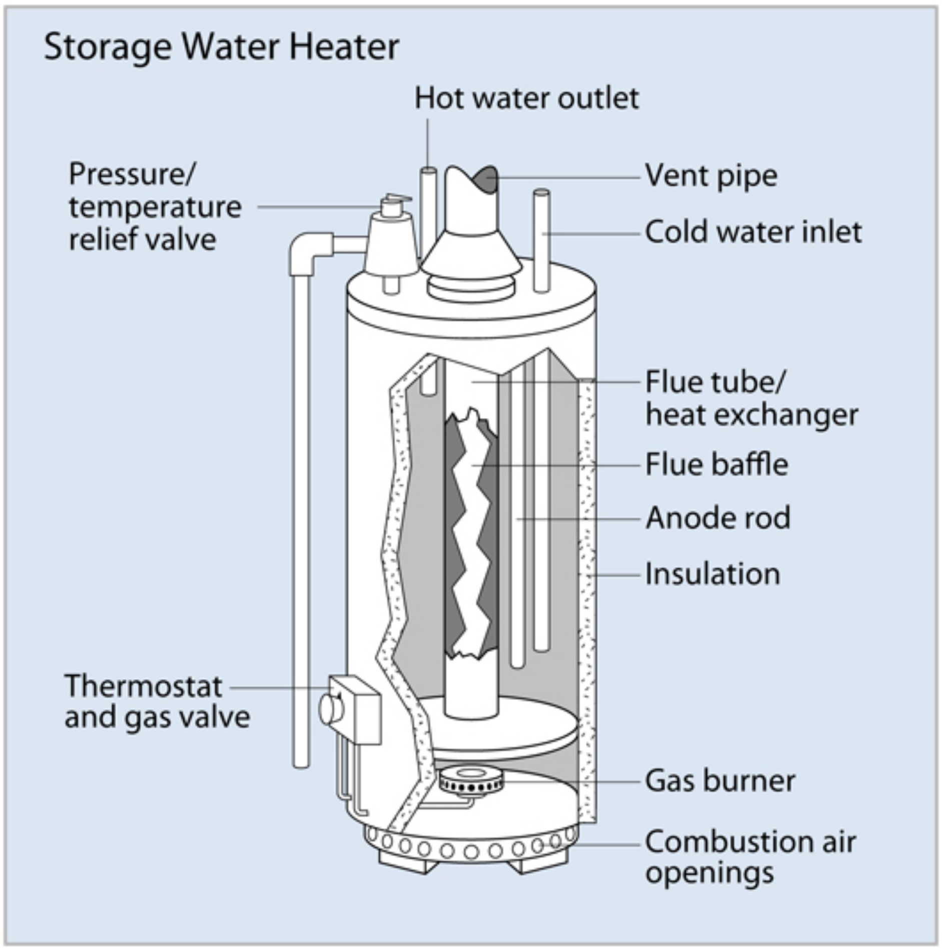
US Primary Energy Consumption (Annual) ≈ 100 Quads

Key Issues for Thermal Storage

- **Time Shift**: Electricity and heat demand do not always coincide
- **Storage Time**: Minutes to months; Insulation free(?)
- **Discharge Time**: Minutes to hours; Heat exchangers systems
- **Energy Density**: High energy density by mass and volume (kWhr/kg, kWhr/L)
- **Low and High**: Both low temperature (273-320 K) and high temperature (≈1000 K) - minimize exergy loss and control heat transfer rates
- **Cost**: $/kWhr, $/kW

Today's Approaches – Sensible Heat

$$Q = \Delta H = mC_p\left(T_2 - T_1\right) \qquad \Delta S = mC_p \ln\left(\frac{T_2}{T_1}\right)$$



Thermal time constant for heat loss

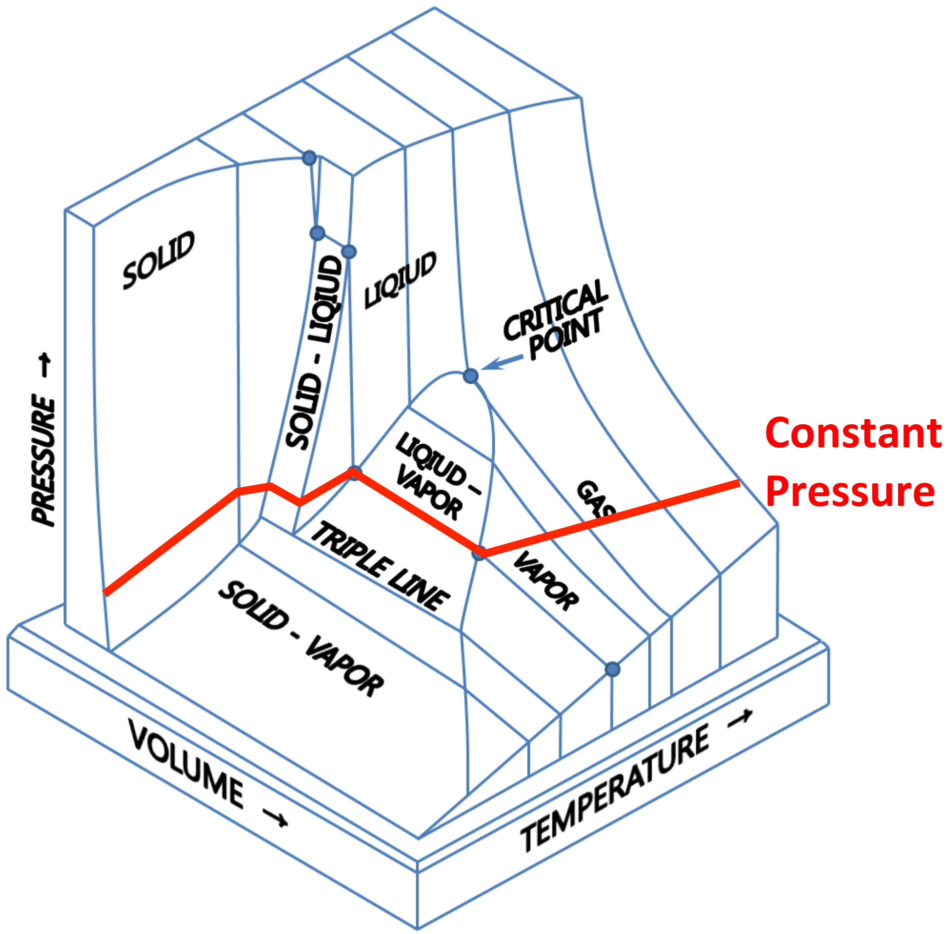
$$\tau = RC = \frac{\rho V C_p}{hA} \sim L\left(\frac{\rho C_p}{h}\right) \sim L\left(\frac{\rho C_p}{k/b}\right)$$

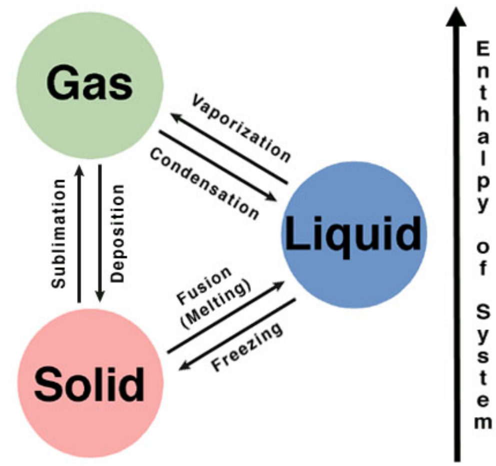
J/cm^3-K

Water at 25 °C	liquid	**4.1796**
Water at 100 °C	liquid	**4.2160**
Aluminium	solid	2.422
Copper	solid	3.45
Granite	solid	2.17
Iron	solid	3.537
Paraffin wax	solid	2.325

Heat loss barrier is kinetic, not thermodynamic

Today's Approaches – Phase Change



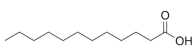


$$\Delta G = \underbrace{\Delta H}_{\text{Heat Storage in Chemical Bonds}} - \underbrace{T\Delta S}_{\text{Increase in Disorder}}$$

During Phase Change at Constant Pressure

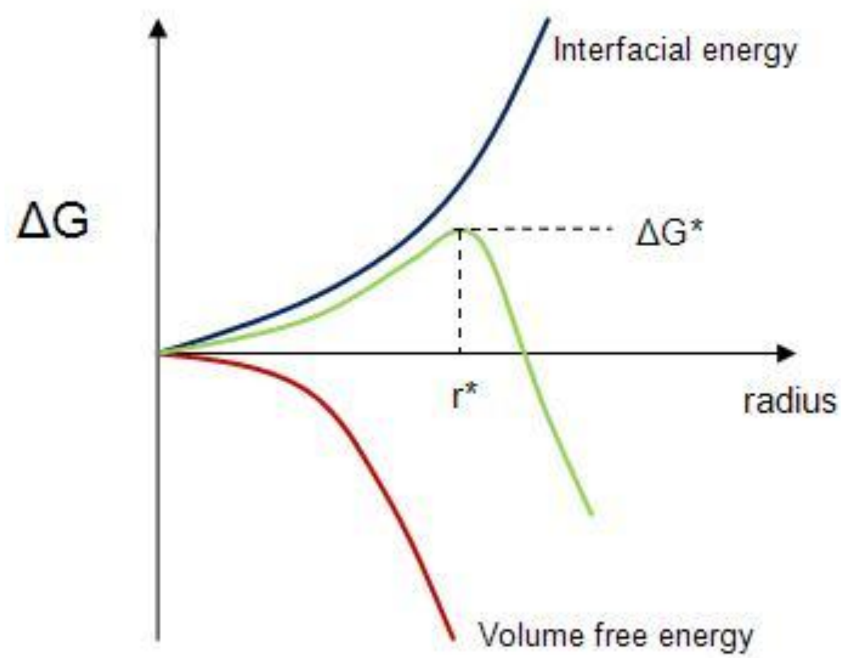
$$\Delta G = 0; \quad T = \frac{\Delta H}{\Delta S}$$

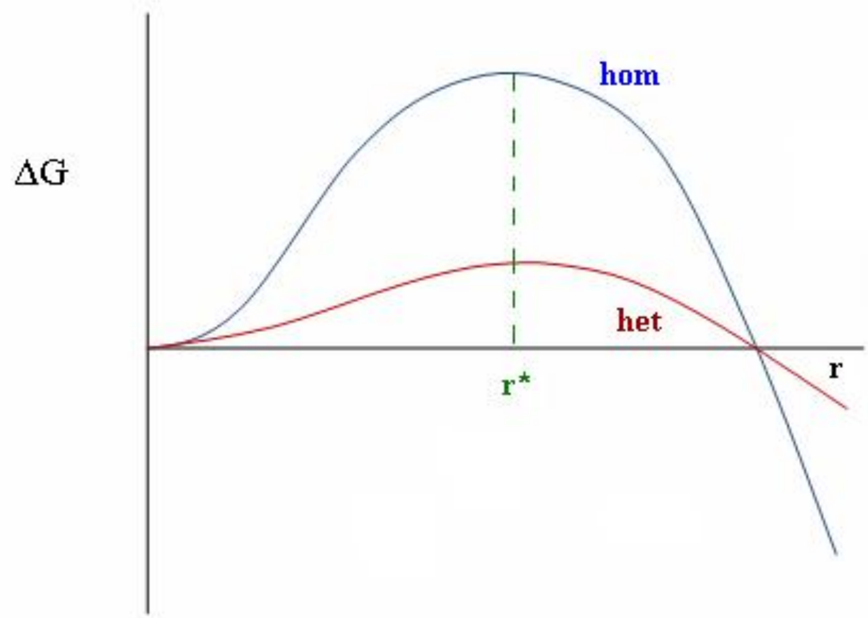
Phase Change Materials

Compound	Melting Point [^oC]	Enthalpy of Fusion [kJ/kg]	Density of Solid/Liquid [kg/m^3]	Boiling Point [^oC]	Enthalpy of Vaporization [kJ/kg]	Density of Liquid/Vapor [kg/m^3]
Water	0	334	917/1000	100	2,258	958/0.6
Lauric Acid 	44	212	1007/862			
Paraffin C_{16}–C_{28}	42–44	190	910/765			
$Na_2SiO_3.5H_2O$	48	267	1450/1280			
$MgCl_2$-$6H_2O$	117	169	1570/1450			
KNO_3	334	266	2110/			
$MgCl_2$	714	452	2140/			
NaCl	800	470	2160/			

Heat Loss Barrier is Nucleation

$$\Delta G = \underbrace{V\Delta h}_{\text{Heat Storage in Chemical Bonds}} - \underbrace{TV\Delta s}_{\text{Increase in Disorder}} + \underbrace{\gamma A}_{\text{Surface Energy}}$$





What else?

Can we control barrier for nucleation?

Can we achieve insulation-free thermal energy storage?

Designer Chemical Reactions & Systems

$$A : B \rightleftharpoons A + B$$

Chemistry Challenge

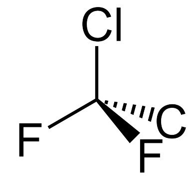
- High Δh (kJ/mol)
- High molar density, ρ (mol/m^3)
- Low change in density: $\Delta\rho/\rho \approx 0$
- Tunable Δs (kJ/mol-K) which gives control of storage temperature, T_{stor}
- Tunable barrier for reverse reaction
  - *Physical separation of A and B*
  - *Catalysis*
- Low-cost of A and B ($/kWhr)
- Non-toxic and non-reactive
- High thermal effusivity, $\sqrt{k \cdot \rho \cdot C}$

Engineering Challenge

- Short heating and recovery time achieved by heat exchanger design & constrained by cost ($/kW)
- Controlled reverse reaction requires design for rapid mass transfer

An Example of Chemistry-Engineering Partnership that Changed the Course of Energy & Environmental History

Stratospheric sink for chlorofluoromethanes : chlorine atomc-atalysed destruction of ozone



CFC-12;
R-12

Mario J. Molina & F. S. Rowland

Department of Chemistry, University of California, Irvine, California 92664

Nature Vol. 249 June 28 1974

Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction

NATURE VOL. 315 16 MAY 1985

J. C. Farman, B. G. Gardiner & J. D. Shanklin

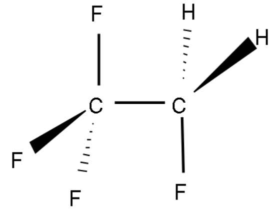
British Antarctic Survey, Natural Environment Research Council, High Cross, Madingley Road, Cambridge CB3 0ET, UK

Vienna Convention for the Protection of the Ozone Layer: 1985

Montreal Protocol on Substances That Deplete the Ozone Layer: Initiated Sept. 16, 1987, enacted Jan. 1, 1989.

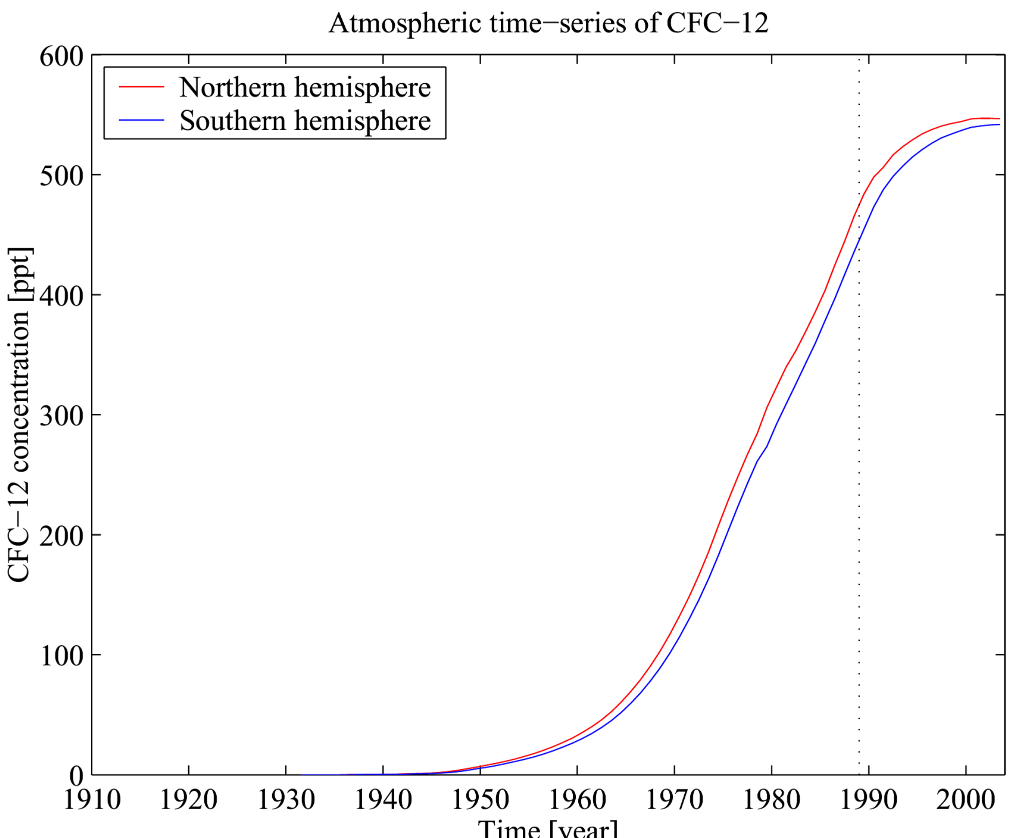
Mario Molina, F. Sherwood Rowland, Paul Crutzen – 1995 Nobel Prize in Chemistry

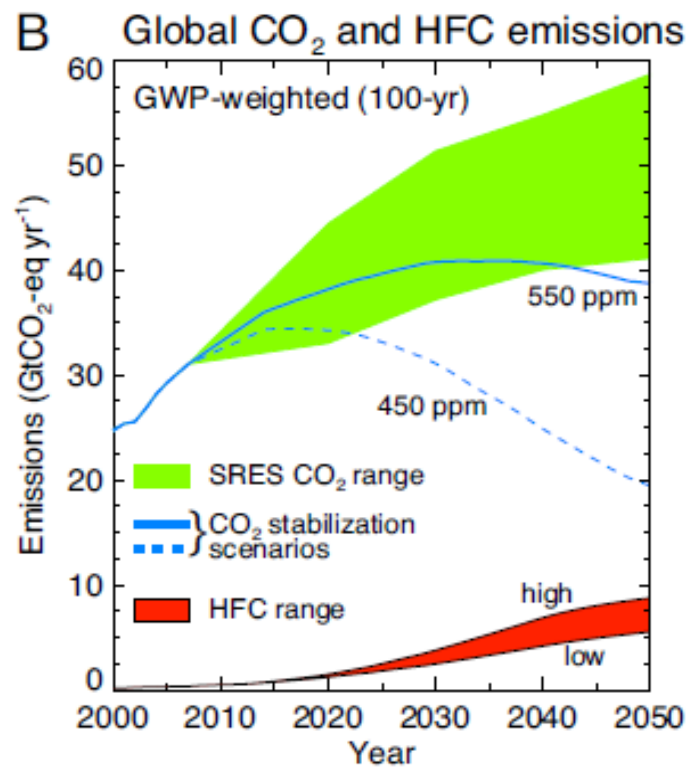
Development of HFCs for Air Conditioning & Refrigeration



1,1,1,2-Tetrafluoroethane, R-134a

Started being used in early 1990s





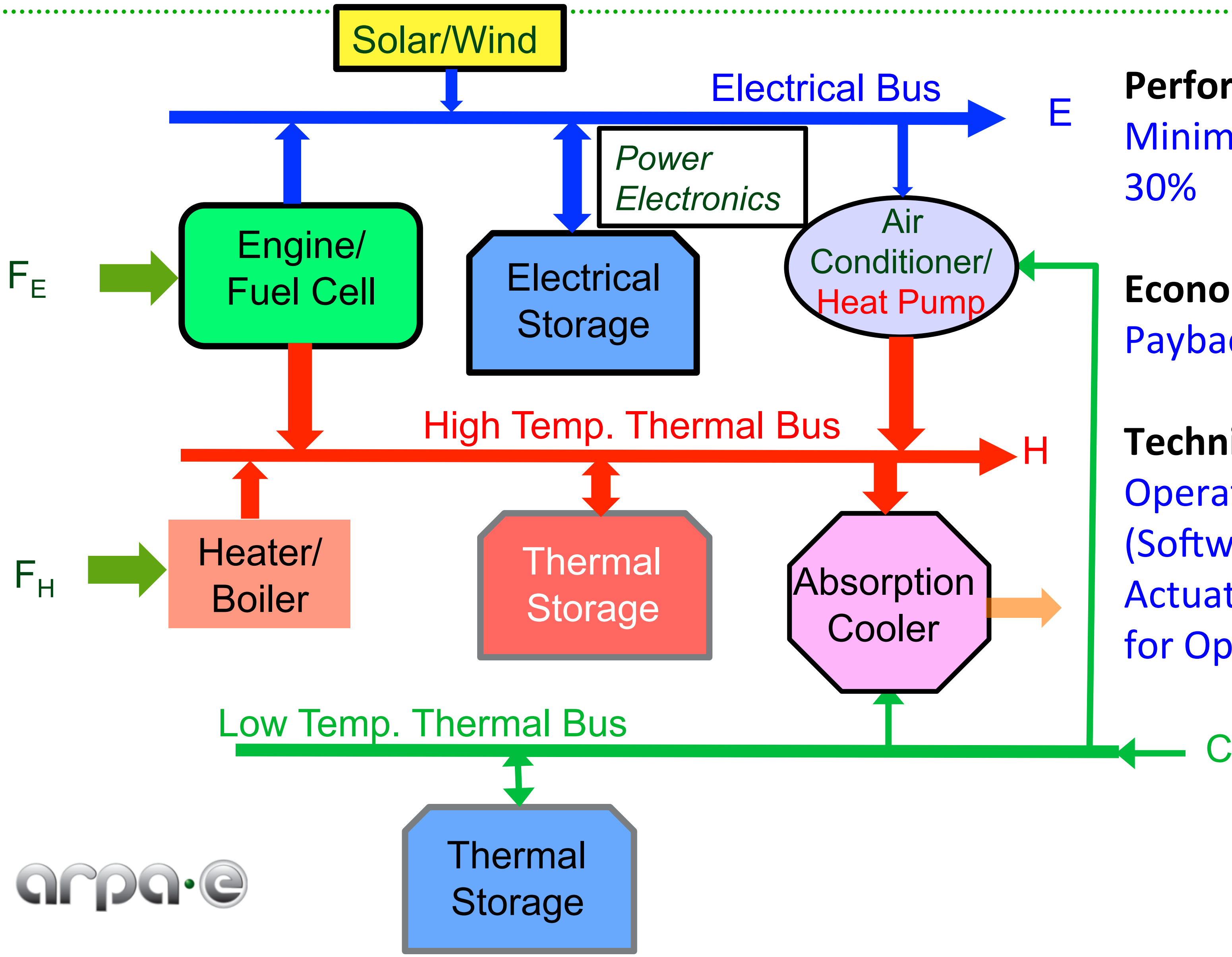
Velders et al, PNAS 106, 10949 (2009

Science-Engineering Partnership for Thermal Energy Storage

Can we tune and control interplay between ΔH, ΔS, ρ, $\Delta\rho$, effusivity in the presence of engineering constraints of cost, toxicity, reliability, …. ?

- Chemical reactions
  - ✧ Gas (hydrogen, methane,…) storage technology for thermal storage
  - ✧ Binding of gases/liquids with ionic liquids or metalorganic frameworks (MOFs)
- Magnetic dipoles
- Electric monopoles – ions in solution/plasma
- Electric dipoles

Integrated Energy Supply Systems:
New Systems Architecture



Performance Goal:
Minimize F by at least 30%

Economic Goal:
Payback in 4-5 years

Technical Challenge:
Operating System (Software) & Sensors-Actuators (Hardware) for Optimal Operation

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Other Applications


Plug-in hybrids: Use battery and engine heat during use to heat battery during cold-weather startup

Electric vehicles: Heat generated during battery charging used for heating and air conditioning of passenger space

Grid-level electricity storage: High-temperature thermal storage + subsequent conversion by engines at < $100/kWhr

Refrigerated trucks and LNG Transport

Efficient use of heat in carbon capture plants

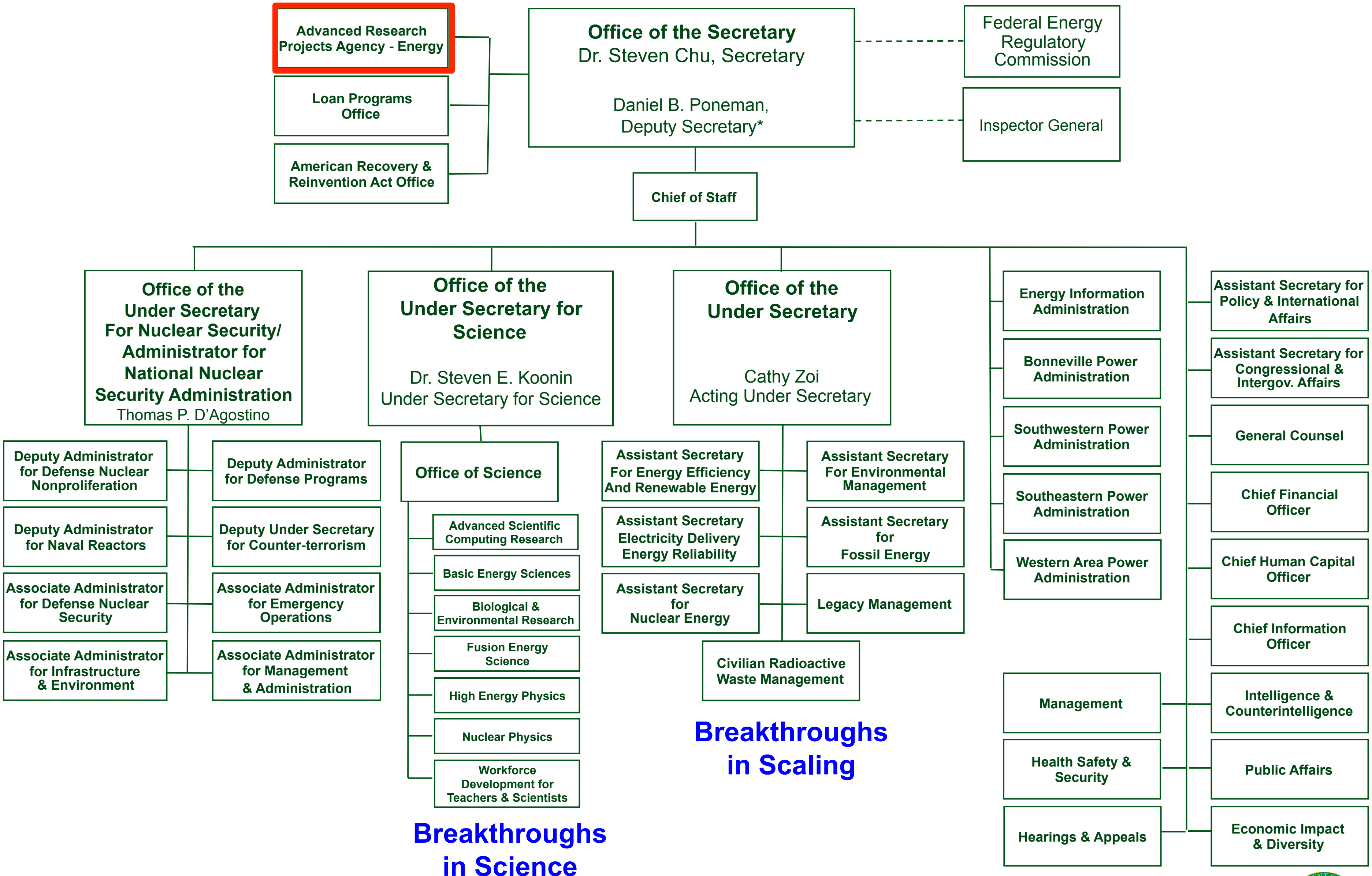
Nuclear: Heat storage for peak power

Brief Overview of ARPA-E

Catalyzing Energy Breakthroughs to Secure America's Future

DOE ORGANIZATIONAL CHART

Breakthroughs in Technology



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* The Deputy Secretary also serves as the Chief Operating Officer

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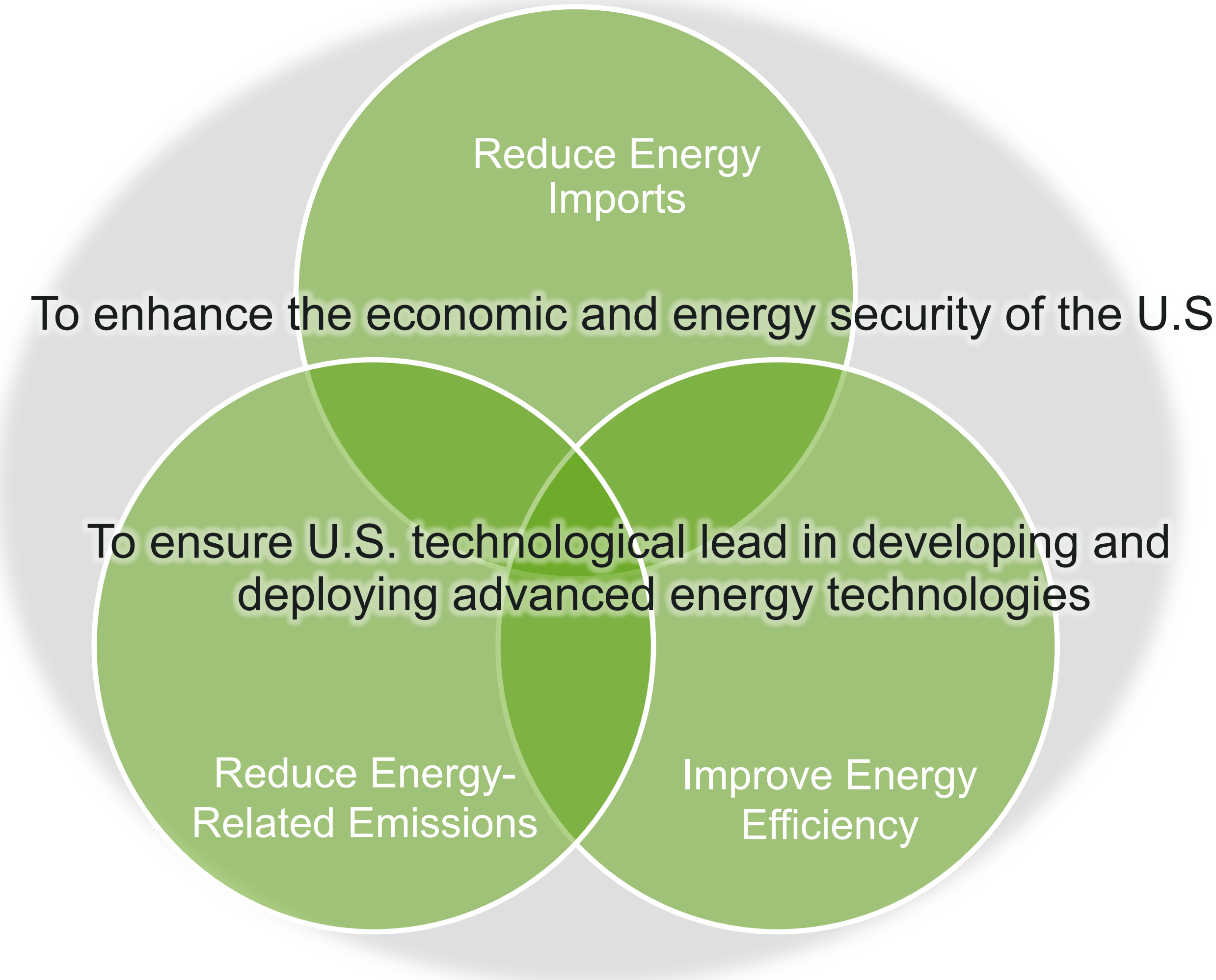
ARPA-E’s Mission & Means



To overcome the long-term and high-risk technological barriers in the development of energy technologies.

(A) identifying and promoting revolutionary advances in fundamental sciences; **AND**

(B) translating scientific discoveries and cutting-edge inventions into technological innovations; **AND**

(C) accelerating transformational technological advances in areas that industry by itself is not likely to undertake because of technical and financial uncertainty.

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Technology Push – Market Pull

Applied Science and Technology

ARPA-E Programs

- $30-40M
- 3 years
- 10-20 projects (large, seedlings)

Integrated Energy Systems

Market

ARPA-E Programs

Broad Solicitation

Transportation

Electrofuels

BEEST

End-Use Efficiency

BEETIT

Stationary Power

GRIDS

IMPACCT

ADEPT

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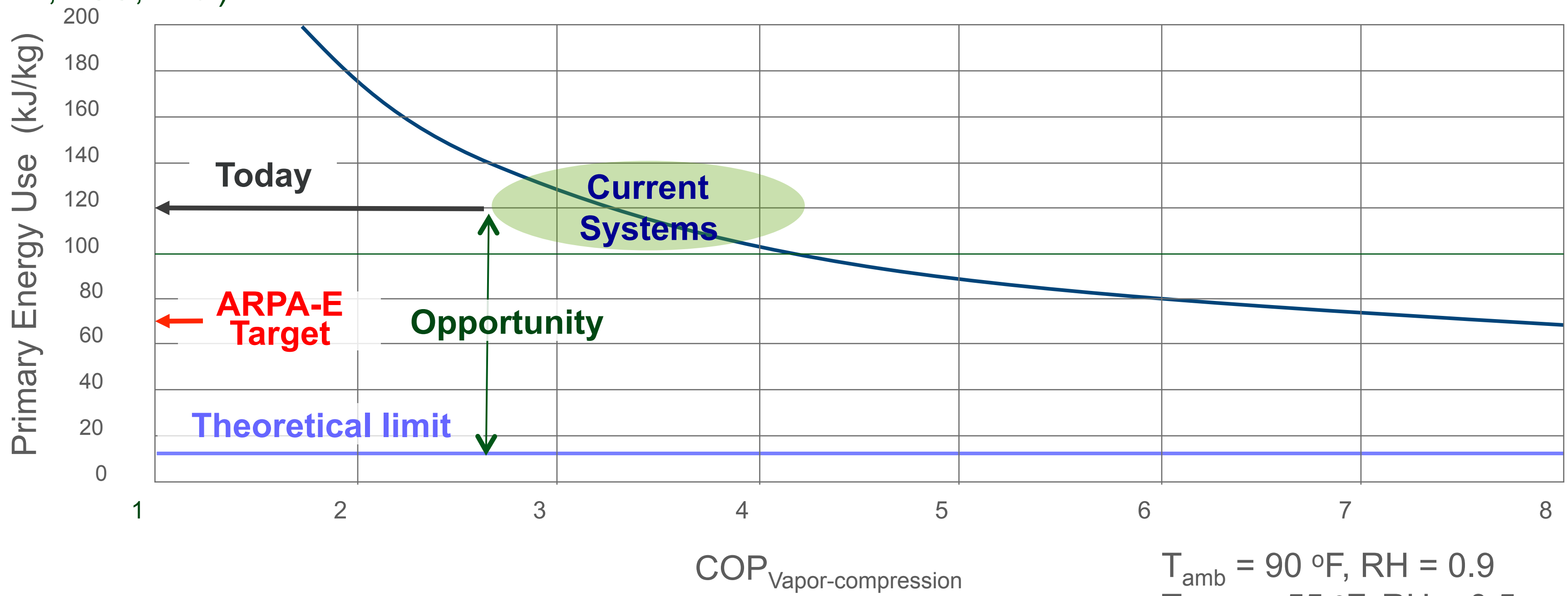
Building Energy Efficiency Through Innovative Thermodevices (BEETIT)

Dr. Ravi Prasher

(MechE, ASU; Intel)

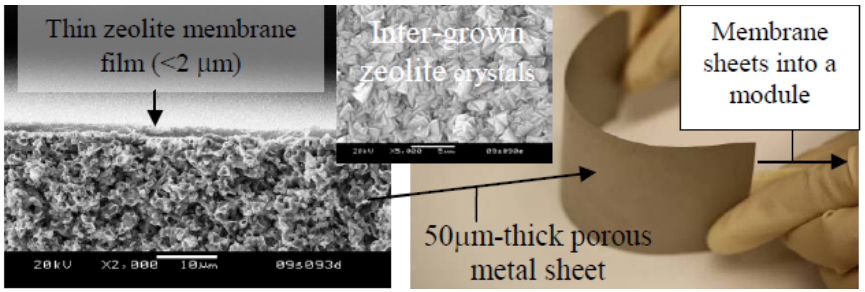
Building cooling is responsible for ~5% of US primary energy consumption and CO_2 emissions

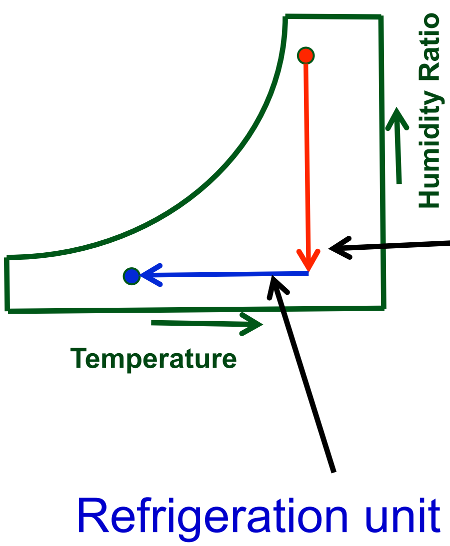


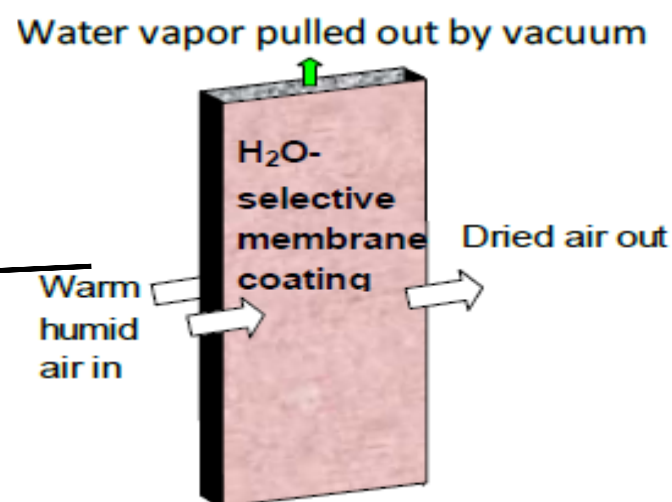
Reduce primary energy consumption by ~ 40 – 50%

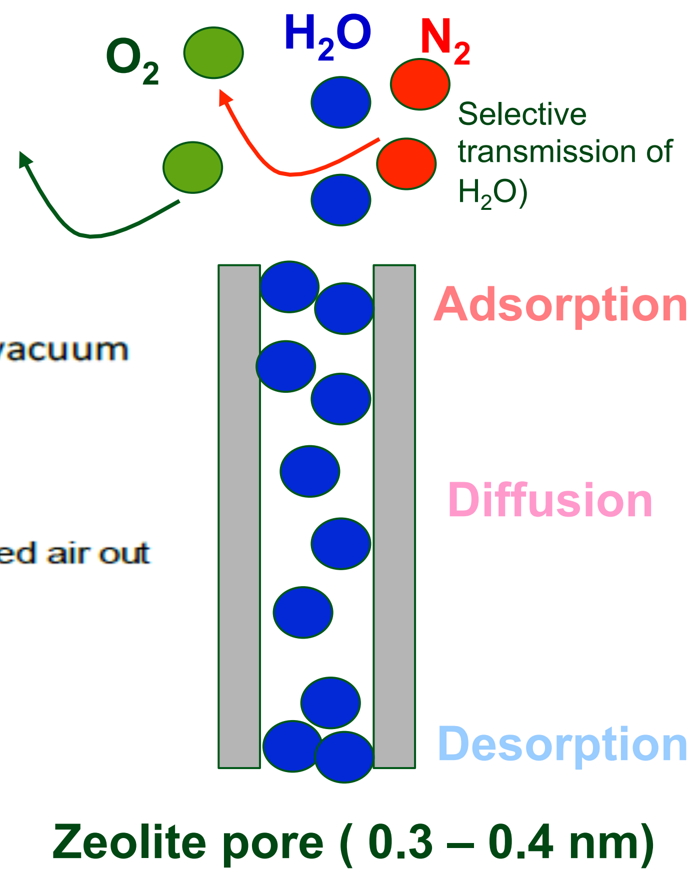
Source: Velders et al, PNAS 106, 10949 (2009)

High-Efficiency, on-Line Membrane Air Dehumidifier Enabling Sensible Cooling for Warm and Humid Climates









Can potentially beat FOA target by ~50%

What is an ARPA-E Project?

IMPACT

If successful, project could have:

- High impact on ARPA-E mission areas
- Large commercial application

BREAKTHROUGH TECHNOLOGY

Technologies that:

- Do not exist in today's energy market
- Are not just incremental improvements; could make today's technologies obsolete

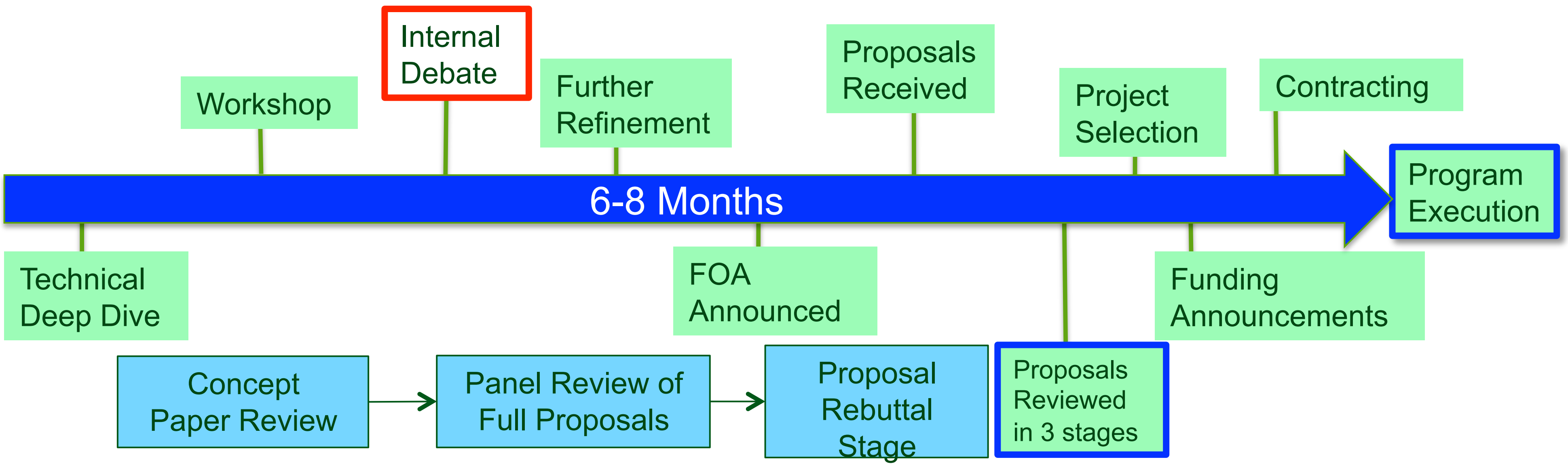
ADDITIONALITY

- Difficult to move forward without ARPA-E funding
- But able to attract cost share and follow-on funding
- Not already being researched or funded by others

PEOPLE

- Best-in-class people
- Teams with both scientists and engineers
- Brings new people, talent and skill sets to energy R&D

ARPA-E DNA: Speed and Efficiency



Recruiting Program Directors (3-4 Years Term)

- Scientific and engineering rigor, depth & breadth
- Intellectual flexibility to move into new fields
- Creativity and openness to new approaches
- Span science/engineering and technology development, with understanding of business/markets
- Serve the nation at a critical time and make national/global impact
- Funding level is $30-40M per program